

N 64 10361

Reprinted from THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 34, No. 9, 988-991, September, 1963  
Printed in U. S. A.**Two-Component Microbalance for Measuring the Forces on Ion-Bombarded Surfaces**

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(Received 21 January 1963; and in final form, 13 May 1963)

A two-component null-type microbalance has been developed to measure forces due to ion bombardment on a surface. The balance employs the principle of the attracted disk electrometer. The sensitivity can be adjusted by simply changing the location of the center of gravity. Measurements of a few micrograms of force in two perpendicular directions can be made simultaneously.

**INTRODUCTION**

**F**ORCES resulting from molecular and ionic bombardment modify the trajectory and attitude of space vehicles. Changes in the trajectories can be used in determining atmospheric densities. It is possible to simulate in the laboratory this free-molecule flow regime of the vehicle through the use of ion and molecular beam apparatus. Single-component balances have been constructed for measuring drag in nearly free-molecule flow<sup>1,2</sup> but since the momentum accommodation coefficients may vary with angle of incidence, two-component data are necessary to describe completely the interactions between ions and molecules and the surface of a space vehicle.

In order to measure the forces on flat metal plates subjected to ion bombardment, a two-component null-reading microbalance was designed and constructed using

the principle of the attracted disk electrometer. This balance is capable of measuring forces of 2-3  $\mu\text{g}$  in one direction and 4-5  $\mu\text{g}$  in the perpendicular direction, the difference probably being due to an unsymmetrical quartz suspension fiber. The balance was designed for the study of ion-surface interactions in the free-molecule flow region and has been used with ion beams with energies from 0.5 to 4 keV.

In general the operation of the balance involves the balancing out of the force imparted by the ion beam with an electrostatic force between two sets of parallel plates. By use of plates of known areas and separations, the ion forces are calculated directly from the electrical potential differences between plates necessary to null the balance.

**BALANCE PRINCIPLE**

The two perpendicular force-measuring components of the balance (normal and tangent to the target) operate on the principle of electrostatic attraction. The essential members of each set are a fixed circular plate electrode supported by an insulator and a movable circular plate electrode attached, by means of the quartz rod network, to the target under ion bombardment. The arrangement is shown schematically in Fig. 1. The movable plate is surrounded by a guard ring at the same potential as the movable plate. The electrodes and target are at the same perpendicular distance from the pivot point of the suspension. The arrangement of the electrodes forms an electrical condenser; and if the distance  $S$  between plates is small compared to the size of the plates, the capacitance will be very nearly  $C = \epsilon_0 A / S$  in vacuum,  $A$  being the effective area of the plates.

The energy required to raise one plate to the potential  $V_1$  and the other to the potential  $V_2$  will be

$$E = \frac{1}{2} C (V_1 - V_2)^2 = \frac{1}{2} (\epsilon_0 A / S) (V_1 - V_2)^2.$$

If the movable plate is given a small displacement,  $V_1$  and  $V_2$  being held constant, there will be a change in the energy of the condenser which will be equal to the mechanical work needed to displace the plate,

$$dE = F dS,$$

$$F = dE/dS = A (V_1 - V_2)^2 / \pi S^2 (7.06 \times 10^2),$$

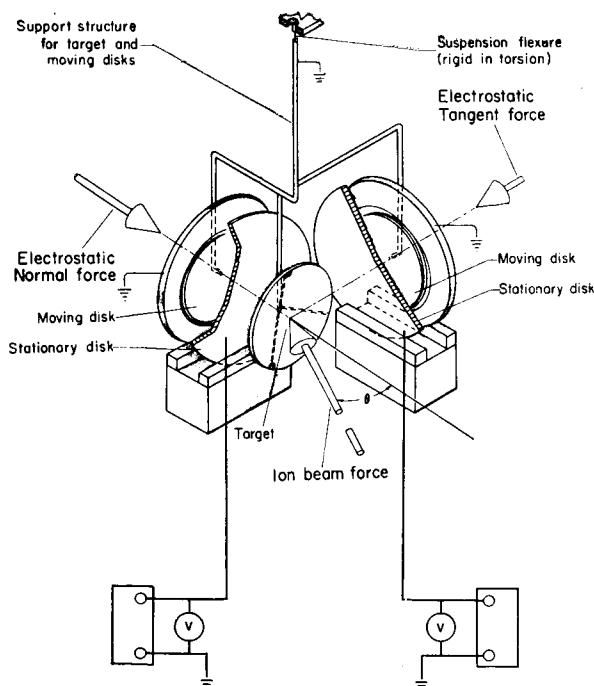


FIG. 1. Two-component electrostatic compensating force system.

<sup>1</sup> J. R. Stalder, G. Goodwin, and M. O. Creager, "A Comparison of Theory and Experiment for High-Speed Free-Molecule Flow," NACA Rep. 1032, 1951.

<sup>2</sup> I. Estermann and E. D. Kane, J. Appl. Phys. 20, 608 (1949).

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when  $(V_1 - V_2)$  is in volts and  $F$  in micrograms. Thus if the movable plate is displaced due to the force of the ion bombardment of the target, the potential difference between the fixed and movable plates required to restore the plates to their original separation gives the force due to the ion bombardment. In the present balance the plates have a separation of 3.14 mm and the movable plates have an effective area of 545 mm<sup>2</sup>. Thus a force of 10  $\mu$ g requires a potential difference of approximately 20 V to balance and a 100- $\mu$ g force requires a potential difference of approximately 65 V to balance.

It has been assumed that all the lines of force are straight and normal to the plane of the disk. However, a few lines stray into the gap between the guard ring and the movable plate. They may be assumed to divide equally between the guard ring and the movable plate, and therefore the effective area of the plate is equal to the area of the plate plus one-half the area of the gap.

The entire electrode system is shielded from the ion beam, and the ion beam from the electrodes, by a copper sheet (not shown in the figures). The shield and the movable plates with guard rings and the target are normally at ground potential, but they may be raised to a positive potential so that the ion beam energy can be reduced without reducing the ion current. With the present ion beam apparatus,<sup>3</sup> the current drops rapidly for ion extraction energies less than about 1 keV.

#### SUSPENSION SYSTEM

The movable element is constructed as shown schematically in Fig. 2 and is made, for the most part, of 1-mm fused-quartz rod suspended by a flexure fiber which was drawn in place and is 50 to 60  $\mu$  in diameter. The movable element (quartz cross, quartz rod network, and moving disks) is an integral rigid structure (i.e., a compound pendulum). The unique feature of the balance is the flexure fiber which not only supports the movable element but also provides high torsional rigidity in addition to high bending flexibility. The entire suspension system as well as the fixed electrodes was coated with gold by the vacuum evaporation process. The gold coating prevents the buildup of any electrostatic charge, provides a path for the ion current, and is the conductor that maintains the moving disks at the same potential as the guard rings. The entire suspended system is balanced so that the center of gravity is very slightly below the flexure. The center of gravity (and thus the sensitivity) is adjusted by changing the mass of the top counterweight. A measure of the sensitivity is found from the period of oscillation of the system, high sensitivity corresponding to a long period.

The assembly and geometric alignment of the balance are precise. When the cross hair and quartz cross are

<sup>3</sup> M. Bader, F. C. Witteborn, and T. W. Snouse, "Sputtering of Metals by Mass-Analyzed  $N_2^+$  and  $N^+$ ," NASA TR R-105, 1961.

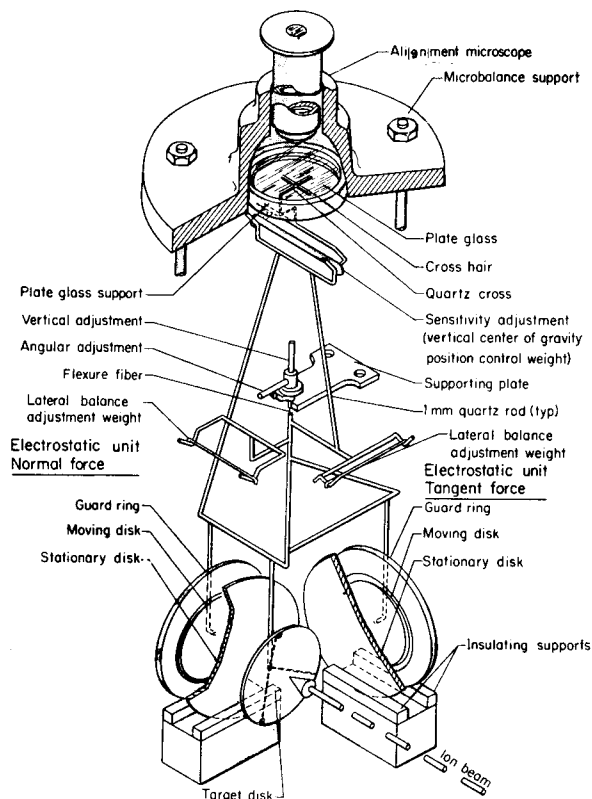


FIG. 2. Balance suspension and electrode systems.

coincident (the null position), the disks of the electrostatic units are parallel and of known spacing. Mass balance of the suspension is achieved by the two lateral adjustment weights. A fine adjustment is made with metal or quartz hangers. Since the balance is of the null type, the final alignment is made in the evacuated balance housing, by applying appropriate potentials to the electrostatic units.

#### HOUSING AND OPTICS

The vacuum housing for the balance (Fig. 3) was constructed so that the balance could be rotated on an O-ring seal to allow the ions to impinge on the target at any desired angle. The housing was also made so that the balance could be traversed perpendicularly to the ion beam in order to align the beam with the center of the target. The balance could also be raised or lowered for the same purpose and was provided with a set of bubble levels to keep the instrument level.

The optical system permitting observation of the alignment of the cross hair and quartz cross consists of a microscope with an appropriate vacuum seal and an adjustable illuminating light located outside the vacuum housing. The light was adjusted so that a narrow bright line was obtained of the quartz cross to facilitate alignment with the cross hair.

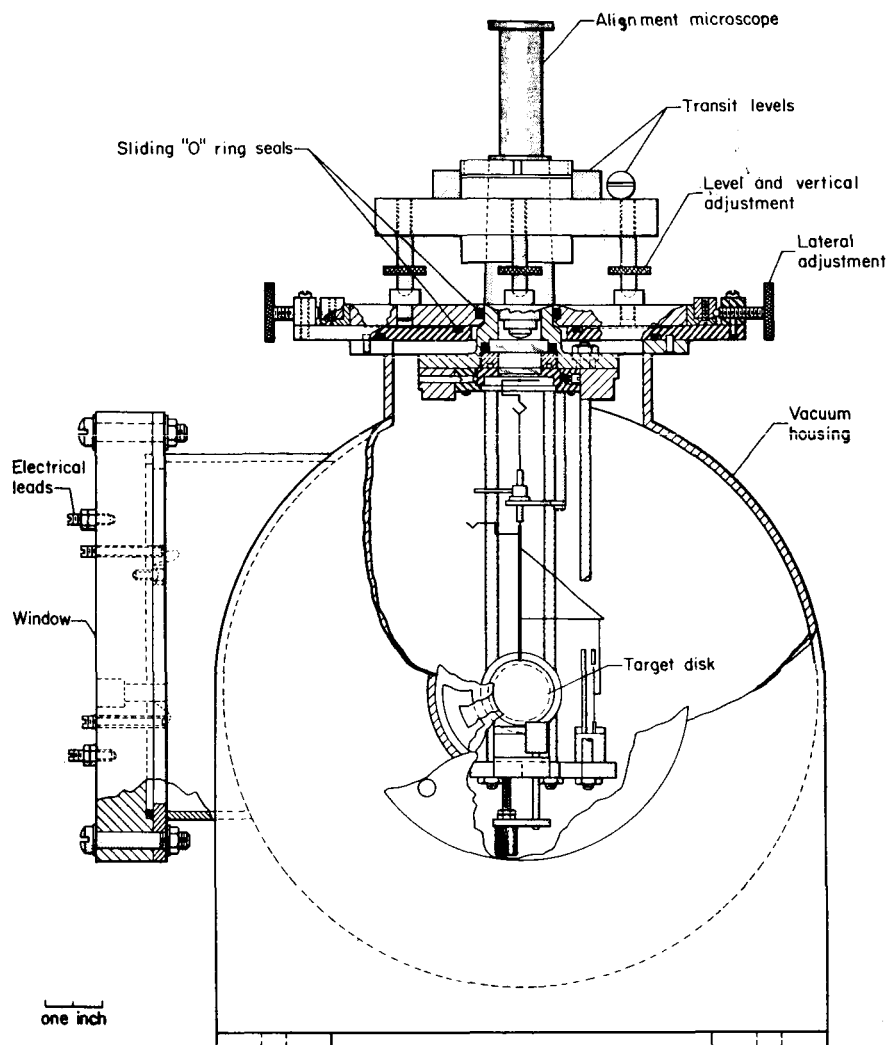


FIG. 3. Balance housing.

#### BALANCE OPERATION

To make force measurements, after the center of gravity has been adjusted for the desired sensitivity, the system is evacuated and the ion beam focused on a probe a few centimeters in front of the target. The potentials of the two fixed electrodes are then adjusted so that the plates are at the proper separation, that is, so that the cross hair and quartz cross are accurately aligned. The ion beam is then focused on the target and the potentials of the two fixed plates are again adjusted to pull the movable plates back to the proper separations. The ion beam is then removed from the target and the zero force potentials checked again to determine any drift. From these potentials the two components of the force are determined.

The minimum detectable forces were determined by observing the movement of the quartz cross as potential differences were applied to the sets of parallel plates. For the greatest conveniently usable sensitivity, the balance is capable of measuring forces of  $2\text{--}3\text{ }\mu\text{g}$  in one direction and  $4\text{--}5\text{ }\mu\text{g}$  in the perpendicular direction, the difference

probably being due to an unsymmetrical quartz suspension fiber. Greater sensitivities can be achieved, but as the point of instability is approached it is very difficult and tedious to obtain a null. Further, the sputtering away of the target material under ion bombardment tends to increase the sensitivity of the balance by raising the center of gravity of the suspension. Thus, for target materials which have high sputtering rates, frequent adjustment is required.

Because of the sensitivity of the instrument, it was necessary to shock-mount the entire ion beam apparatus in order to eliminate vibrations due to the operation of nearby machinery.

After considerable practice it was possible to obtain a force reading approximately 1 min after the ion beam was turned on the target. If the voltages of the fixed plates are increased by approximately the proper amount at just the time the ion beam is allowed to strike the target, a null can be obtained with a minimum of movement of the suspension system. It was found that forces up to about  $150\text{ }\mu\text{g}$  were easily measured whereas forces greater than about  $200\text{ }\mu\text{g}$

were difficult to measure without allowing the suspension to be forced against either the guard rings or the mechanical stop. The zero-force reading would frequently shift due to the slight movement of the counterbalance weights if the suspension system were allowed to hit the guard rings or the mechanical stop. During operation with intense beam powers, there was frequently a shift of about 4 to 5  $\mu\text{g}$  in the normal force zero readings between the beginning and end of a force reading. This shift is believed to be related to the heating of the target material since it was always in the same direction and did not appear in the tangential force component. Distortions of the target due to thermal effects could shift the mass in a direction to affect the normal force component.

#### DATA AND ERRORS

A typical set of two-component data is shown in Fig. 4. Each data point shown represents the mean of at least six force readings, each involving two zero-force readings. The data illustrate the consistency of the measurements and give an indication of the magnitude of the random errors of the measurements. Results of measurements for several ion-metal combinations have been obtained.

The errors are of both constant and random nature. The constant error results from the uncertainty in the value of the effective areas of the plates and their separation distance. This error was estimated to be approximately  $\pm 1.5\%$  of the measured force. The random errors of aligning the quartz cross with the cross hair were determined by measuring the same force a number of times. The probable error of the mean of the readings taken for a data point is of the order of  $\pm 1.5 \mu\text{g}$  in the normal force and  $\pm 0.5 \mu\text{g}$  in the tangential force. These errors are

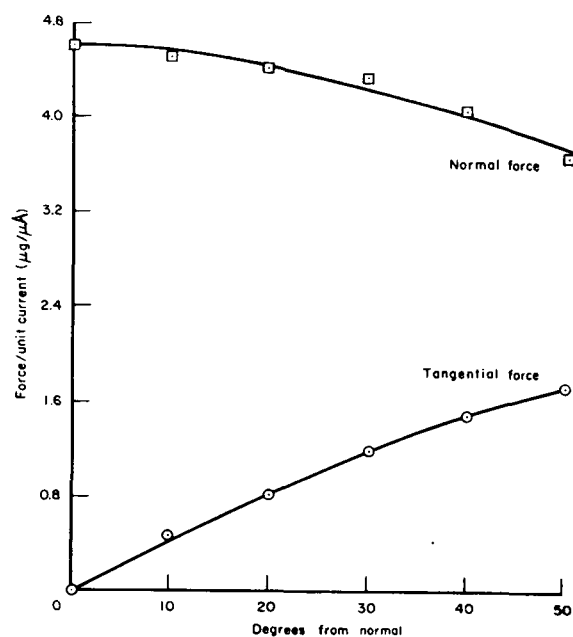


FIG. 4. Measured components of force on a copper target bombarded with 2-keV  $\text{N}_2^+$  ions.

variable due to the particular condition, experience, and patience of the operator.

The fluctuations in the output current of the rf ion source varied with the ion used as well as with the ion energy. Thus the errors involved in reading the ion current were energy and ion dependent and ranged from about  $\pm 0.5$  to  $\pm 2\%$ . The magnitudes of the ion currents were of the order of 10 to 40  $\mu\text{A}$ . Alignment and focusing difficulties could also have contributed to the scatter of the data of Fig. 4.